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The design of the positron source for the Next Linear Collider (NLC) is presented. The key features of this design include accelerating positrons at an L-band frequency (1428 MHz) and using a rotating positron target with multi-stage differential pumping. Positron yield simulations show that the L-band design yields at the source 2.5 times the beam intensity required at the interaction point and is easily upgradable to higher intensities required for the 1 TeV NLC upgrade. Multibunch beam loading compensation schemes in the positron capture and booster accelerators and the optics design of the positron booster accelerator are described. For improved source efficiency, the design boasts two parallel positron vaults adequately shielded from each other such that one serves as an on-line spare.

1 Introduction

The NLC is designed to collide a 90-bunch positron beam with an identical electron beam with a bunch intensity as high as 1.25×10^{10} particles for each machine pulse [1,2]. The beam pulse intensity requirement for the NLC represents more than a 20-fold increase over its SLC counterpart! While the SLC positron source [3], by virtue of its relative design simplicity and its proven operational reliability, is used as a design basis for NLC, significant changes are made to greatly boost the positron beam intensity to meet the NLC needs. In this paper, we will first present a design overview, then concentrate on the important aspects of the design and report on the progress made in the design since the writing of our previous paper [4].

2 Design Overview

The NLC positron source is of a conventional type based on $e^{\pm}$ pair production from an electromagnetic shower created in a thick, high-Z target upon bombardment by high energy electrons. Three subsystems comprise the NLC source: a drive beam electron accelerator, a positron production and collection system, and a positron booster linac. Table 1 summarizes the important parameters of the NLC positron source for both its phase-I design and its phase-II upgrade (500 GeV and 1 TeV center-of-mass energy, respectively).

The drive beam accelerator uses S-band (2856 MHz) RF for acceleration and has an injector consisting of a thermionic gun, two subharmonic and one S-band bunchers. The positrons are generated in a $W_{75}Re_{25}$ target, adiabatically phase-space transformed in a flux concentrator and a tapered-field solenoid, and captured in an L-band (1428 MHz) accelerator embedded inside a 0.5-T uniform-field solenoid. Acceleration of the positron beam to 2 GeV for emittance damping occurs in an L-band booster accelerator with a dense array of quadrupole magnets providing transverse focusing.

Table 1. NLC Positron Source Parameters

Parameters	NLC-I	NLC-II
Drive Electron Beam:		
Electron Energy (GeV)	3.11	6.22
No. of bunches per pulse	90	90
Bunch Intensity	1.5×10^{10}	1.5×10^{10}
Repetition rate (Hz)	180	120
Beam power (kW)	121	161
Beam σ on target (mm)	1.2	1.6
Pulse Energy Density ρ (GeV/mm^2)	4.6×10^{11}	5.2×10^{11}
Positron Target:		
Material	$W_{75}Re_{25}$	$W_{75}Re_{25}$
Thickness (R.L.)	4	4
Energy deposition (J/pulse)	126	188
Power deposition (kW)	23	23
Positron Collection:		
Tapered field (T)	1.2	1.2
Uniform field (T)	0.5	0.5
Flux concentrator field (T)	5.8	5.8
Flux concentrator minimum radius (mm)	4.5	4.5
Accel. RF frequency (MHz)	1428	1428
Accel. gradient (MV/m)	25	25
Minimum iris radius (mm)	20	20
Edge Emittance (m·rad)	0.06	0.06
Collection efficiency (%)	19%	17%
Positron yield per electron	1.4	2.1
Positron bunch Intensity	2.1×10^{10}	3.2×10^{10}

The L-band design for the NLC positron capture and booster accelerators is the key to achieving the order of magnitude higher positron beam intensity over that of the SLC positron source. By quadrupling the transverse phase space admittance and boosting the longitudinal phase space admittance as well, it not only immediately provides a >4-fold increase in the positron capture efficiency, but ultimately ensures the upgradability of the source to NLC-II intensities, with a large intensity safety margin.

In operation, system reliability is always a critical issue. The reliability of the positron production and capture system is particularly important since the high radiation levels in these areas would prevent human access for prompt repair in case of hardware failure during a physics run. In addition to engineering the best possible reliability into each component, a most effective way to mitigate the reliability problem is to build redundancy into the system. In our proposal, two side-by-side positron vaults housing identical positron production and capture systems that are adequately shielded from each other will be built. If one system fails, we may immediately switch over to the other to continue the run. In the meantime, we may wait for the radiation level in the vault with failed hardware to drop and then repair the failed component(s). As long as the mean time to fail exceeds the mean time to repair, which we hope will be the case based on the superior reliability demonstrated by the SLC positron source, such a redundancy design will ensure excellent reliability.

3 Target Engineering

By the nature of this design, the positron target that serves the dual purposes of generating an electromagnetic shower upon electron bombardment and inducing $e^\pm$ pair production must absorb a considerable amount of energy from the drive beam. The drive beam energy density must be kept below a critical threshold, which depends on the target material, or excessive single pulse beam heating may cause the target to fail. As in the SLC positron source, $W_{75}Re_{25}$ is chosen as the target material because of its high $e^\pm$ pair production efficiency and excellent thermo-mechanical properties. Target R&D at SLAC using 20–25 GeV drive electrons and 5–7 R.L. (radiation length) thick targets [5] established a failure threshold for $W_{75}Re_{25}$ due to single pulse beam heating at

$$\rho_{\max} = \frac{N_{-}E_{-}}{2\pi\sigma^2} = 1\times10^{12}\,\frac{\mathrm{GeV}}{\mathrm{mm}^2}, \tag{1}$$

where N_{-} is the number of drive electrons per pulse, E_{-} the energy of the electrons, and σ the rms radius of the electron beam. Thus, the rms beam radius at the target has been chosen to be 1.2 mm for NLC-I and 1.6 mm for NLC-II, respectively, to keep the beam energy density per pulse about 50% below this threshold.

The $W_{75}Re_{25}$ target, shaped into a ring with an outer radius of 25 cm and a radial thickness of 0.7 cm, will be rotated at a frequency of 2 Hz. In this way, areas of successive beam pulse impacts on the target will be adequately separated and the target will be heated uniformly. Unlike other types of target motions such as trolling, the rotating motion preserves the geometry of the target with respect to the incident drive beam and the emerging $e^\pm$ beams as well. Therefore, it is expected to eliminate positron beam intensity modulations that might be induced if the target motion is such that its geometry with respect to the beam changes periodically, as in the SLC source. The target will be cooled from the inner ring surface to which a silver or copper casting containing stainless steel cooling tubes is brazed. With a cooling water flow rate of ~2 l/s and a velocity of ~10 m/s, the steady state temperature of the target is estimated to be ~400°C for the cases of both NLC-I and NLC-II, which is a rather comfortable temperature for $W_{75}Re_{25}$.

The rotating motion along with the necessity to cool the target leads to a design in which the target is attached to a rotating shaft that passes from vacuum where the target resides to atmosphere where a driving motor is connected and cooling water is coupled in and out. The high radiation levels near the target precludes the use of conventional vacuum seals made of organic materials such as viton. Instead of pursuing a vacuum-tight seal, we propose to use multi-stage differential pumping along the length of the shaft with radiation resistant seals that limit conductance relying on tight clearances (<15 μm) between sealing surfaces and long path lengths. Candidate seals include axial and radial face seals, axial and radial labyrinth seals, and magnetic face seals.

Figure 1 depicts a conceptual design of the positron target system with three stages of differential pumping. In such a three-stage design, the first stage could use an oil-free dry scroll pump, the second and third stages could each use a turbomolecular pump backed by a dry scroll pump. If the pressure drops by three orders of magnitude after each stage, which we have reason to believe, then, such a design could easily realize the desired 10^{-7} Torr vacuum in the target chamber. A test two-stage differential pumping system with a rotating shaft will be built and experimented to prove the feasibility of this design and also to select the best seals.

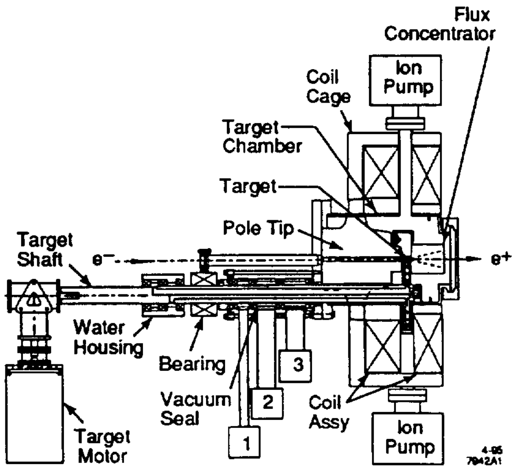

Figure 1. A conceptual design of the NLC positron target system with three stages of differential pumping.

4 Capture and Booster Accelerators

The capture accelerator is required to quickly accelerate the positron beam to relativistic energies to minimize debunching due to the initial huge energy spread. As electrons are also accelerated along with positrons, it also must be able to handle up to 14 A of multibunch beam loading current in the case of NLC-II. In our design, two 5-m detuned L-band (1428 MHz) structures with an average gradient of 25 MV/m will be used for acceleration, and two 3-m L-band structures sandwiched in between will be used for beam loading compensation by operating off-frequency at 1428 ± 1.428 MHz (i.e., the ΔF method). Each of the acceleration and compensation structures will be driven by two 75-MW L-band klystrons with SLED-I pulse compression. The beam will be focused by a long DC uniform-field solenoid with a 0.5 T axial field that encloses all four structures.

The 250-MeV positron beam emerging from the capture accelerator will be injected into the booster linac after an achromatic and isochronous bend doublet, which also allows the electron beam to be separated from the positron beam and dumped. The booster linac, designed to accelerate the beam to 2 GeV, consists of 12 accelerating modules. Each module contains two 5-m detuned L-band structures with a minimum iris radius of 20 mm and will be powered by two 75-MW L-band klystrons feeding one SLED-I cavity. The unloaded gradient is about 20 MV/m. Beam loading in the booster linac, with a maximum loading current of 2.75 A, will be accomplished by using the ΔT method, i.e., injecting the beam before the structure is completely filled. In contrast to the ΔF method, the ΔT method offers the advantage of not introducing a large single-bunch energy spread, thus minimizing chromatic emittance growth. The booster linac has roughly a 15% energy headroom.

The lattice for the booster linac is designed using TRANSPORT up to second order. It consists of a dense array of FODO cells whose spacing is scaled approximately as $\sqrt{E}$ along the linac except for the first structure where the cell spacing is kept constant. Most of the quadrupole magnets have apertures large enough to surround the L-band structures, with one or two small-aperture quadrupoles in between successive structures to match the optics across the gaps. The strengths of the large-aperture quadrupoles are kept nearly the same. The phase advance per cell starts at 60° at the beginning of the lattice and gradually decreases to about 25° at the end. This design leads to a quasi-linear E scaling of the maximum β function. First-order TRANSPORT calculation shows that the positron beam size is shrunk to <15 mm after the first few structures.

Using the program LINACBBU [6], multibunch beam blow-up due to long-range transverse wake field has been calculated for the booster linac. It is concluded that such effects are negligible for structures with a 10% full-range Gaussian frequency detuning.

5 Yield Calculation

The yield for both positrons and electrons from $W_{75}Re_{25}$ targets of thicknesses ranging from 3.5 to 6 R.L. (1 R.L. = 3.43 mm) are calculated using the program EGS [7] for both drive beam energies, i.e., 3.11 and 6.22 GeV. While it is desirable to maximize the positron yield, the volume density of pulse energy deposition in the target must be kept safely below the failure threshold. These considerations leads to the choice for the optimal target thickness to be 4 R.L.. The positron and electron yields per drive electron from such a target are, respectively, 7.2 and 9.0 for 3.11 GeV drive electrons, and 12.5 and 17.1 for 6.22 GeV drive electrons. About 18% and 14% of the drive beam energies are deposited in the target for 3.11 and 6.22 GeV beams, respectively.

The particle rays obtained from the EGS simulation are traced through the adiabatic phase space transformer and the capture accelerator, whose parameters are listed in Table 1, using the program ETRANS [8]. The best positron yield at the exit of the capture accelerator where the beam reaches an energy of about 250 MeV is found to be 1.4 and 2.1 per drive electron for NLC-I and NLC-II, respectively, after applying 6-dimensional phase space admittance cuts. Correspondingly, the positron beam intensities at the 250 MeV point are 2.1×10^{10} /bunch and 3.2×10^{10} /bunch, respectively, each exceeding the respective maximum desired bunch intensity at the IP (i.e., 0.85×10^{10} and 1.25×10^{10}) by a factor of 2.5.

Using the program TURTLE, the positron rays are further traced through the booster linac, whose alignment is assumed to be perfect. After applying a 0.06 m-rad transverse emittance cut and a $\pm2\%$ energy spread cut, it is found that beam transmission through the booster linac is about 95%. While structure and magnet misalignments are inevitable in a real machine, the transverse and energy admittances of the pre-damping ring with an energy compressor are 0.09 m-rad and $\pm3\%$, respectively, or 1.5 times greater than the cuts applied to the rays traced to the end of the linac. These two factors have offseting effects on the beam transmission. Thus, the large intensity safety margins after the capture accelerator are almost fully preserved to the end of the booster linac.

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